

**APPLICATION FOR
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FOR

HIGH DENSITY OPTICAL PACKAGING

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HIGH DENSITY OPTICAL PACKAGING

RELATED APPLICATION

5 [0001] This application is related to, and claims priority from, U.S. Provisional Patent Application Serial No. 60/326,455, entitled "High Density Optical Packaging", filed on October 3, 2001, the disclosure of which is incorporated here by reference.

BACKGROUND

10 [0002] From the advent of the telephone, people and businesses have craved communication technology and its ability to transport information in various formats, e.g., voice, image, etc., over long distances. Typical of innovations in communication technology, recent developments have provided enhanced communications capabilities in terms of the speed at which data can be transferred, as well as the overall amount of data being transferred. As these capabilities improve, new content delivery vehicles,
15 e.g., the Internet, wireless telephony, etc., drive the provision of new services, e.g., purchasing items remotely over the Internet, receiving stock quotes using wireless short messaging service (SMS) capabilities etc., which in turn fuels demand for additional communications capabilities and innovation.

20 [0003] Recently, optical communications have come to the forefront as a next generation communication technology. Advances in optical fibers over which optical data signals can be transmitted, as well as techniques for efficiently using the bandwidth available on such fibers, such as wavelength division multiplexing (WDM), have resulted in optical technologies being the technology of choice for state-of-the-art long haul communication systems.

25 [0004] For long haul optical communications, e.g., greater than several hundred kilometers, the optical signal must be periodically amplified to compensate for the tendency of the data signal to attenuate. For example, in the submarine optical communication system 10 shown in Figure 1, the terrestrial signal is processed in WDM terminal 12 for transmission via optical fiber 14. Typically, each system 10 is

implemented using a number (e.g., 2, 4, 6, 8, 10, 12, etc.) of pairs of optical fibers. Periodically, e.g., every 75 km, a repeater 16 (sometimes referred to as a “repeater”) amplifies the transmitted signal so that it arrives at WDM terminal 18 with sufficient signal strength (and quality) to be successfully transformed back into a terrestrial signal.

5 [0005] Conventionally, erbium-doped fiber amplifiers (EDFAs) have been used for amplification in the repeaters 16 of such systems. As seen in Figure 2(a), an EDFA employs a length of erbium-doped fiber 20 inserted between the spans of conventional fiber 22. A pump laser 24 injects a pumping signal having a wavelength of, for example, approximately 1480 nm into the erbium-doped fiber 20 via a coupler 26. This
10 pumping signal interacts with the f-shell of the erbium atoms to stimulate energy emissions that amplify the incoming optical data signal, which has a wavelength of, for example, about 1550 nm. One drawback of EDFA amplification techniques is the relatively narrow bandwidth within which this form of resonant amplification occurs, i.e., the so-called erbium spectrum. Future generation systems will likely require wider
15 bandwidths than that available from EDFA amplification in order to increase the number of channels (wavelengths) available on each fiber, thereby increasing system capacity.

[0006] Distributed Raman amplification is one amplification scheme that can provide a broad and relatively flat gain profile over a wider wavelength range than that which has
20 conventionally been used in optical communication systems employing EDFA amplification techniques. Raman amplifiers employ a phenomenon known as “stimulated Raman scattering” to amplify the transmitted optical signal. In stimulated Raman scattering, as shown in Figure 2(b), radiation from a pump laser 24 interacts with a gain medium 22 through which the optical transmission signal passes to transfer
25 power to that optical transmission signal. One of the benefits of Raman amplification is that the gain medium can be the optical fiber 22 itself, i.e., doping of the gain material with a rare-earth element is not required as in EDFA techniques. The wavelength of the pump laser 24 is selected such that the vibration energy generated by the pump laser beam’s interaction with the gain medium 22 is transferred to the transmitted optical
30 signal in a particular wavelength range, which range establishes the gain profile of the pump laser.

[0007] Although the ability to amplify an optical signal over a wide bandwidth makes Raman amplification an attractive option for next generation optical communication systems, the use of a relatively large number of high power pump lasers (and other components) for each amplifier in a Raman system has hitherto made EDFA amplification schemes the technology of choice for long haul optical communication systems. However, as the limits of EDFA amplification are now being reached, recent efforts have begun to explore the design issues associated with supplementing, or replacing, EDFA amplification technology with Raman amplification technology.

[0008] In order to design a wideband, Raman-amplified optical communication system, however, a much larger number of active and passive optical and electrical components need to be housed in each repeater 16 than were previously needed in conventional submarine optical communication systems. Additionally, the amount of optical fiber, and the number of fiber splices, needed to interconnect the optical components will also increase dramatically. For example, Applicants have estimated that implementation of an eight fiber pair, wideband, Raman-amplified optical communication systems may require repeaters which have 150-300 (or more) lasers, 500 to 800 (or more) passive optical components, 1000-2000 meters of optical fiber and 600-900 (or more) optical splices.

[0009] Even as the number of components, length of fiber and amount of power needed to operate those components has increased, the physical size of the repeater 16 is restricted by, for example, operational, deployment, transportation and storage considerations. Thus, according to exemplary embodiments of the present invention, it is preferable to design structures and techniques for accommodating the aforedescribed optical components and fiber (as well as other components) within a repeater 16 having substantially the dimensions (in millimeters) illustrated in Figure 3.

[0010] These, and other, design considerations and constraints dictate a need for new, high density optical packaging which will enable next generation, high power optical communication systems to be deployed.

BRIEF SUMMARY OF THE INVENTION

[0011] These, and other, drawbacks, limitations and problems associated with conventional optical communication systems are overcome by exemplary embodiments of the present invention, wherein a repeater for use in an undersea optical communication includes a pressure vessel, a frame, disposed within the pressure vessel, for holding optical signal amplification circuitry and other circuitry, wherein the optical signal amplification circuitry includes at least 500 passive optical components packaged within the frame and which is interconnected by at least 1000 meters of optical fiber.

[0012] According to exemplary embodiments of the present invention, an optical component tray includes a plurality of cavities for holding fiber optic components, an area for winding optical fiber and at least one guide groove extending between said area and each of said plurality of cavities.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Figure 1 is a schematic diagram of an optical communication system in which the present invention can be implemented;

[0014] Figure 2(a) is a conceptual diagram of a conventional erbium-doped fiber amplifier;

[0015] Figure 2(b) is a conceptual diagram of a conventional Raman amplifier;

[0016] Figure 3 is a depiction of a repeater showing dimensions thereof;

[0017] Figure 4 is a block diagram of an exemplary terminal unit of an optical communication system including link monitoring equipment according to exemplary embodiments of the present invention;

[0018] Figure 5 is a block diagram of an exemplary repeater of an optical communication system in which the present invention can be implemented;

[0019] Figure 6 is another block diagram of an exemplary repeater of an optical communication system including an exemplary Raman pumping architecture;

[0020] Figures 7(a) and 7(b) depict the various shell layers associated with repeaters according to exemplary embodiments of the present invention;

[0021] Figure 8 illustrates an exploded view of one end of a repeater having a pressure vessel joint according to an exemplary embodiment of the present invention;

[0022] Figures 9(a)-9(e) depict various exemplary seams for dielectric layers according to exemplary embodiments of the present invention;

[0023] Figures 10(a)-10(b) depict an exemplary repeater inner frame structure fabricated from a dielectric material according to an exemplary embodiment of the present invention;

[0024] Figure 11 shows an exemplary optical architecture which can be employed by repeaters according to an exemplary embodiment of the present invention;

[0025] Figure 12 illustrates a more detailed schematic of an exemplary 4x4 coupler which can be used in the optical architecture of Figure 11;

[0026] Figure 13 depicts functional blocks of a repeater power distribution scheme according to one exemplary embodiment of the present invention;

[0027] Figure 14 shows a top and bottom view of a line assembly according to an exemplary embodiment of the present invention;

[0028] Figure 15 depicts an optical package which can be used to house components employed by line assemblies according to exemplary embodiments of the present invention;

[0029] Figure 16 shows a laser diode mounting assembly according to exemplary embodiments of the present invention;

[0030] Figure 17(a) shows another optical package which can be used to house components and optical fiber according to exemplary embodiments of the present invention;

[0031] Figure 17(b) shows an alternative fiber handling tray which can be used in conjunction with the optical package of Figure 17(a);

[0032] Figures 18(a)-18(e) illustrate other exemplary optical component and fiber packaging techniques according to the present invention;

[0033] Figure 19 depicts the mounting arrangement of two line assemblies into a line pair assembly according to an exemplary embodiment of the present invention;

[0034] Figure 20 is a cutaway portion illustrating the fiber ways between line assemblies in a line pair assembly according to exemplary embodiments of the present invention;

[0035] Figure 21 shows the mounting arrangement between two line pair assemblies to create a line quad assembly according to exemplary embodiments of the present invention;

[0036] Figure 22 is a cutaway portion illustrating the fiber ways and power connections for an exemplary line quad assembly according to the present invention;

[0037] Figure 23 is an exploded view of an exemplary repeater populated with four line quad assemblies according to the present invention; and

[0038] Figure 24 is a sectional view that shows a plurality of line quad assemblies mounted in a repeater according to an exemplary embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

[0039] In the following description, for the purposes of explanation and not limitation, specific details are set forth, such as particular systems, networks, software, components, techniques, etc., in order to provide a thorough understanding of the present invention. However, it will be apparent to one skilled in the art that the present invention may be practiced in other embodiments that depart from these specific details. In other instances, detailed descriptions of known methods, devices and circuits are abbreviated or omitted so as not to obscure the present invention.

[0040] Repeaters which enable high power optical signal transmission systems can be employed in systems such as those depicted in Figure 1, i.e., submarine optical communication systems, or in terrestrial systems. For the purpose of illustration, rather than limitation, an exemplary Raman-amplified system is described below for context. Those skilled in the art will appreciate that many different system configurations could also utilize repeater designs, structures and techniques according to the present invention.

[0041] An exemplary architecture for terminal 12 and 18 is provided in the block diagram of Figure 4. Therein, the long reach transmitters/receivers (LRTRs) 30 convert terrestrial signals into an optical format for long haul transmission, convert the undersea optical signal back into its original terrestrial format and provide forward error correction. The WDM and optical conditioning unit 32 multiplexes and amplifies the optical signals in preparation for their transmission over cable 34 and, in the opposite

direction, demultiplexes optical signals received from cable 34. The link monitor equipment 36 monitors the undersea optical signals and undersea equipment for proper operation. The line current equipment 38 provides power to the undersea repeaters 36. The network management system (NMS) 40 controls the operation of the other components in the WDM terminal, as well as sending commands to the repeaters 36 via the link monitor equipment 36, and is connected to the other components in the WDM terminal via backplane 42.

[0042] Functional blocks associated with an exemplary repeater 16 are depicted in Figure 5. Therein, each fiber has a splitter 50 connected thereto to sample part of the traveling WDM data signal. The splitters 50 can, for example, be implemented as 2% couplers. A photodetector 52 receives the sampled optical signal from its respective splitter 50 and transforms the optical signal into a corresponding electrical signal. The photodetector 52 outputs the electrical signal to a corresponding sub-carrier receiver unit 54, which detects and decodes the commands present in the sub-carrier modulated monitoring signal that has been modulated on the envelope of the WDM data signal. Although this exemplary embodiment describes the transmission of supervisory information using a sub-carrier modulated onto the envelope of the WDM data signal, those skilled in the art will appreciate that other techniques can be employed to send supervisory data between terminals and repeaters, e.g., using a separate WDM channel for supervisory signaling.

[0043] After decoding the command, the particular sub-carrier receiver 54 determines whether the decoded command is intended for it. If so, the action in the command is executed, e.g., measuring the power of the WDM signal, measuring the pump power output from one or more lasers in the pump assembly, or changing the supply current to the lasers of the pump assembly. To this end, the sub-carrier receivers 54 are connected to respective current control and power monitoring units (I settings) 56, which each include pump power monitors and pump current controls for each laser in the associated pump laser assembly 58.

[0044] The pump modules 58 provide pump light into the optical fibers to amplify the data signals traveling therein using a Raman amplification scheme, as generally described above. The gain profile for a single pump wavelength has a typical

bandwidth of about 20-30 nm. For high capacity WDM communication applications, such a bandwidth is too narrow and, accordingly, multiple pump wavelengths can be employed to broaden the gain profile. Figure 6 depicts an exemplary pump architecture for providing multiple pump wavelengths in a Raman amplification scheme.

5 [0045] Therein, a number N of pump radiation sources 110 are optically coupled to a respective one of N pump radiation combiners 112. Each of the pump radiation sources 110 generate various pump wavelengths at various pump powers using individual radiation emitters 114. The individual radiation emitters 114 can, for example, be lasers, light emitting diodes, fiber lasers, fiber coupled microchip lasers, or
10 semiconductor lasers. The combiners 112 combine the various outputs of their respective pump radiation sources, e.g., by wave division multiplexing, and outputs the combined optical pumping signal to coupler 118. Coupler 118 can be an NxM coupler which takes contributions from all N inputs to provide a representative output at each of M output ports. Energy from the coupler 118 is pumped into the optical fiber(s) via
15 pump signal combiners 122. In general, Raman pump architectures couple the light generated by pump lasers at various wavelengths and various powers to the optical fibers to pump the optical data signals. Those skilled in the art will appreciate that many other types of pumping architectures can be employed to provide Raman amplification to optical data signals in accordance with the repeater structures described below.

20 [0046] Figure 7(a) illustrates the general shell structure of a repeater 16 according to the present invention from a layered perspective. Specifically, the outer layer 200 is part of the pressure vessel that protects the interior structure and optical/electrical components from a multitude of stresses, both before and after deployment underwater. Desirable physical characteristics for the pressure vessel include high strength, good
25 resistance to corrosion and good thermal conductivity, i.e., to aid in minimizing temperature rises within the repeater due to heat dissipation. This latter characteristic of repeaters according to the present invention is emphasized in a number of features described below to aid in maintaining high performance of the lasers operating therein. Exemplary materials from which the pressure vessel can be fabricated include
30 beryllium-copper alloys (e.g., 1.9% Be) and tungsten alloys, although any materials having the aforementioned characteristics can be used. Pressure vessels according to

the present invention can, for example, be approximately 1200 mm long, have an outer diameter of about 380 mm and a wall thickness of about 30 mm.

[0047] Inside of the pressure vessel layer 200 is a dielectric layer 202 that electrically insulates the pressure vessel from the optical/electrical components housed therein.

5 Applicants anticipate that repeaters 16 operating in next generation, high power optical communication systems, e.g., Raman systems, may require more than 40 kV to be supplied thereto. Accordingly, the dielectric layer 202 should have a relatively high breakdown voltage while at the same time having a high thermal conductivity. Selection of an appropriate dielectric material given the need for high breakdown
10 protection and thermal conductivity in repeaters according to the present invention is discussed in more detail below. The thickness of the dielectric layer 202 can, for example, be about 6 mm.

[0048] Inside of the dielectric layer 202, resides an inner frame structure 203. In the example of Figure 7(a), this inner frame structure 203 is depicted in four sections 204,
15 206, 208 and 210. However, as described below, the number of elements which make up the frame structure is not particularly important and it can be fabricated from more or fewer than four elements. For example, as seen in Figure 7(b), the inner frame 203 can be constructed from two elements 211 and 213. If multiple elements are used for the inner frame structure 203, then those elements can be connected using, for example,
20 a tongue and groove mechanism as seen in Figure 7(b). The inner frame structure 203 provides an area within which the optical/electrical components are mounted, the optical fiber is run and the various power connections are made. Several detailed examples of suitable mounting assemblies will be described below.

[0049] Having provided an overview as to the various layers found in repeaters 16
25 according to the present invention, various features of the present invention that enable repeaters to perform high power optical communication according to the present invention will be discussed individually below.

[0050] Referring now to Figure 8, an exemplary pressure vessel assembly according to an exemplary embodiment of the present invention is depicted in an exploded view.
30 Therein, various components that are used to removably seal one end of the pressure

vessel 200 can be seen. The elements shown therein are designed to seal the interior of the pressure vessel 200 against water, while at the same time provide an entry/exit for the power cable and optical fibers (not shown in this figure). The pressure vessel assembly includes a C-ring 210, a pressure vessel endcap 212 with at least one gasket 214, a breech ring 216 having engagement elements 230, a bell housing 218 having engagement elements 236 and a gimbal 220. For more details regarding an exemplary pressure vessel which can be used in conjunction with repeaters according to the present invention, the interested reader is directed to commonly assigned, copending U.S. Patent Application Serial No. _____, entitled "Repeaters with Pressure Vessels Having Breech Joints", to Perry Pitrone et al., filed on October 3, 2001, the disclosure of which is incorporated here by reference.

[0051] Manufacturing of the aforescribed elements of pressure vessel assemblies according to the present invention can be accomplished in a number of different ways. For example, the pressure vessel 200 and endcap 212 can be forged and post machined. Since no flanges are provided for endcap attachment, extrusions and rolled rings can be used for the cylindrical section from which the pressure vessel is machined, which reduces machining waste associated with flanged forged pressure vessels. The bell housing 218 can be centrifugally cast and post machined. The breech ring 216 can be machined from plate metal stock.

[0052] As mentioned above, a dielectric layer 202 can be inserted between the pressure vessel 200 and inner frame structure 203 to protect the optical/electrical circuitry held in the frame structure against the very large amount of power carried by the power cable to supply each of the repeaters 16. Applicants believe that, depending upon the length of the system, distance between repeaters, power consumption of each repeater and other design variables, it will be desirable to provide more than 40kV, possibly as much as 50-60kV, to the power cable. Accordingly, with a safety margin of, for example, 50% it will be desirable to provide a dielectric layer 202 that has a breakdown voltage of greater than 40kV and, more preferably greater than 75kV, to protect the components held in the inner frame structure 203.

[0053] However, the dielectric layer 202 should also have certain other characteristics. For example, the dielectric layer 202 should fit within an allocated volume. As

mentioned above, volume within the repeaters 16 is at a premium given the competing desires of maintaining a fixed repeater size and providing sufficient optical and electrical components to provide Raman-amplification across a very wide bandwidth (i.e., on the order of 100nm). For this exemplary embodiment, the space allocation for the dielectric layer is approximately 6 mm, however those skilled in the art will appreciate that such an allocation may increase or decrease based upon specific applications. Another desirable characteristic of the dielectric layer 202 is that it should minimize the temperature rise across the material, i.e., it should be a good thermal conductor rather than a strong insulator. Preferably, the thermal conductivity of the dielectric layer should be greater than 1.5 W/mK. Again, this feature of the present invention addresses the issue of the large amount of heat that needs to be dissipated due to the high power of repeaters 16.

[0054] Additionally, it may be useful if the dielectric layer 202 has sufficient elasticity to absorb a certain amount of pressure vessel deflection when the repeater is deployed. Under certain conditions, the pressure on the pressure vessel 200 may be sufficient to deflect the pressure vessel inwardly, e.g., on the order of 0.75 mm. Although such deflection may not be problematic, the selection of the material for the dielectric layer 202 may optionally address this design consideration. Moreover, it is desirable that the dielectric layer be non-hygroscopic, e.g., have a water absorption characteristic of less than 0.1%. Lastly, the selected dielectric layer 202 should also be easy to manufacture and assemble with the other components of the repeater 16.

[0055] Given these considerations, Applicants have studied a number of different materials and fabrication methods for the dielectric layer 202 which are sorted by category in the table below. In addition to those set forth therein, rotational molding can also be used to fabricate dielectric layer 202.

[0056] Materials	[0057] Fabrication Methods		
	[0058] Layering or Wrapping of Sheet Material	[0059] Mold In Situ, Cast Inside Pressure Vessel	[0060] Pre-molded, extruded or injection molded
[0061] Polymers/Thermoplastics	No	No	Yes
[0062] Elastomers/Polyurethanes	Yes	Yes	No
[0063] Epoxy-resin mixtures	No	Yes	No
[0064] Gap Filling Products	No	Yes	No

Table 1

Considering each fabrication method in turn, wrapping the repeater frame 203 with the dielectric material taken from a sheet or roll can be accomplished by cutting a selected material to size and then either bonding the sized material to the inner diameter of the pressure vessel 200 or bonding the sized material to the outer diameter of the frame structure 203. Those skilled in the art will appreciate that employing sheet or roll material to provide dielectric layer 202 may involve one or more layers of the material being applied in practice depending upon the breakdown voltage/mm and other characteristics of the material. If a single layer is used, then the structure of the seam between the ends of the layer should be designed to reduce voltage creepage. Exemplary seam structures for dielectric layer 202 when fabricated using sheet or roll material are illustrated as Figures 9(a)-9(e). Therein, it can be seen that various types of overlap are provided to reduce voltage creep and preserve the dielectric breakdown properties of the layer as a whole. Exemplary material candidates in this category include Furon TC-100 and TC-2000 series materials, Chomerics F-174 material, Berquist Gap Pad 3000 material and Fujipoly GR material.

[0065] The dielectric layer 202 can also be fabricated by molding a suitable material in situ. For example, a liquid resin cast can be provided inside the pressure vessel 200 for molding dielectric layer 202. Exemplary materials for in situ molding of the dielectric layer 202 include Cotronics and Conap materials with or without boron nitride fillers (which increase dielectric and thermal performance) and Berquist Gap Filler 2000 material.

[0066] Another way to provide the dielectric layer 202 is to combine that layer with the inner frame structure 203, i.e., by forming the inner frame structure 203 from a dielectric material that protects the optical and electrical components secured thereto.

10 An exemplary inner frame structure 203 fabricated from a dielectric is illustrated in Figures 10(a) and 10(b). Therein, it can be seen that the slots 280 for receiving the line quad assemblies (not shown here, described in more detail below) are fabricated directly into the dielectric material. Additionally, since the dielectric material of the inner frame 203 in Figures 10(a) and 10(b) will not be as thermally conductive as an inner frame structure fabricated from a metal, conductive struts 300 can be provided in this embodiment to conduct heat generated by the optical and electrical components to the pressure vessel 200. The dielectric inner frame 203 according to these exemplary embodiments can be made as a single part by extrusion, thermoforming or injection molding. The resulting structure can then be inserted into the pressure vessel 200 and bonded thereto. Exemplary materials which are suitable for fabricating a dielectric inner frame structure for repeaters 16 according to the present invention include polymers D2 and RS012 available from Cool Polymers. Such materials exhibit good dielectric and thermal performance (e.g., 30.3 kV/mm and 0.12 degrees C, respectively). For more details, the interested reader is referred to U.S. Provisional Patent Application Serial No. 60/326,429, entitled "Repeater Shell Structure For High Power Optical Communication Systems", to Brent Pohl et al., filed on October 3, 2001, the disclosure of which is incorporated here by reference.

[0067] The inner frame structure 203 secures the optical and electrical components that perform amplification within the pressure vessel 200. According to exemplary embodiments of the present invention, these optical and electrical components have a "line quad" architecture, which means that at least some of the components associated

with providing the optical signal processing functionality for two optical fiber pairs (i.e., two optical fibers carrying optical signal data in the direction from terminal 12 to terminal 18 and two optical fibers carrying optical signal data in the direction from terminal 18 to terminal 12) are shared (either actively or redundantly) and that, therefore, electrical and fiber optic connections are made between each of the line assemblies. The sharing of components between line assemblies is a significant benefit attributable to repeater designs according to the present invention, which features are described in more detail below.

[0068] An exemplary line quad assembly optical schematic is provided as Figure 11.

Therein, line quad 300 includes optical pump assembly 301 (shown enclosed by dashed lines) and transmission fiber 326. The optical pump assembly 301 in this exemplary embodiment includes four contrapropagating (backward) pump radiation sources 310 optically coupled to respective pump combiner assemblies 312, each of which can be disposed on a line assembly (described below with respect to Figure 13. Each of the pump radiation sources 310 has a set of wavelengths λ_{i1} to λ_{imi} , where i designates the i th pump radiation source, and mi is the number of wavelengths generated by the i th pump radiation source. For example, each pump radiation source 310 can employ 10, 12 or 14 backward pump lasers 314. Each pair of pump lasers may be set to provide pump energy at a different pump wavelength and pump power so as to provide a desired overall gain profile to the optical data signal being amplified by each repeater 16. As a purely illustrative example for repeater 16 employing pump radiation sources 310 each having 10 backward pump lasers (20 laser pairs) 314, the wavelength/optical output power can be selected as set forth in Table 2 below.

Laser Pair	Wavelength (nm)	Power/LP (mW)
1	1409.50	45.10
2	1415.50	45.10
3	1426.50	38.00
4	1439.50	43.20
5	1465.00	39.00
6	1409.50	45.10
7	1418.50	43.30
8	1429.50	34.20
9	1443.50	40.70
10	1474.00	33.50
11	1409.50	45.40
12	1421.50	43.30

13	1429.50	34.20
14	1449.00	42.00
15	1498.00	18.20
16	1412.50	45.10
17	1424.50	43.30
18	1439.50	38.30
19	1457.00	42.00
20	1506.00	28.10

Table 2

[0069] The paired pump lasers provide redundancy such that if one of the lasers in a particular laser pair becomes inoperative, then the output power of the remaining laser can be increased so that the overall gain profile is not substantially affected. Between each pump laser 314 and its respective pump radiation combiner 312, a fiber Bragg grating (not shown) can be inserted as a wavelength locker that locks the radiation output from its associated laser 314 to the desired wavelength.

[0070] Each of the four pump radiation combiners 312 combines the radiation at the wavelengths of the set of wavelengths of its respective pump radiation source 310. Each pump radiation source 310 and corresponding pump radiation combiner 312 can be associated with a line assembly as described below. The combination of pump laser outputs within each line assembly can be accomplished in stages by providing a number of pump radiation combiner components within each unit 312. For example, each pair of pump lasers 314 within a pump radiation source 310 can initially be combined using a pump beam combiner (not shown) component. The pump beam combiners combine optical energy from each pair of pump lasers in a manner which depolarizes the resulting pump output. Various examples of techniques for combining the outputs of pump lasers to generated depolarized pump energy are described in co-pending, commonly assigned U.S. Provisional Patent Application Serial No. _____, entitled "Depolarizer for Multiplexed Arbitrarily Polarized Lasers", to Nandakumar Ramanujam et al., filed on October 3, 2001, the disclosure of which is incorporated here by reference.

[0071] The outputs of pairs of pump beam combiners can then be combined by input to a pump wavelength combiner component (not shown), which process can be continued

until all of the pump laser outputs within a line assembly are combined. Other examples of pump radiation combining can be found in co-pending, commonly assigned U.S. Patent Application Serial No. 09/838,218, entitled "A Pump Assembly Employing Coupled Radiation Sources for Multiple Fibers", to William Shieh et al.,
5 filed on April 20, 2001, the disclosure of which is incorporated here by reference.

[0072] The four pump radiation combiner outputs are optically coupled to a 4x4 coupler 318, which combines the outputs of the various pump lasers from each of, in this example, four line assemblies. The 4x4 coupler 318 outputs a set of pump signals via the four coupler outputs 320 to be coupled with the optical data signals transmitted
10 on each of the fibers 326. Because the 4x4 coupler 318 combines the coupled radiation profiles input into the 4x4 coupler, the output from each of the four coupler outputs 320 has the spectral shape of the combined coupled radiation profiles. Therefore, each of the four pump radiation profiles has a contribution from all of the individual wavelengths of four pump radiation sources 310. This enables the pump lasers 316 on
15 each line assembly to be shared among all four line assemblies in the line quad and to provide pumping power to all four of the optical fibers associated therewith.

[0073] An example of a balanced 4x4 coupler which can be used as 4x4 coupler 318 is provided in Figure 12, however the interested reader is referred to co-pending, commonly assigned U.S. Patent Application Serial No. _____, entitled "Balanced
20 Coupler for Radiation Sources", to William Shieh et al., filed on October 3, 2001, the disclosure of which is incorporated here by reference, for more detail. In Figure 12, it can be seen that the 4x4 coupler 318 can be implemented in two sections 350 and 352, each of which can be disposed within a different line assembly (described below). Since these two sections are identical, only section 350 is described herein. The outputs
25 of two of the pump radiation combiner units 312 are input into a first 2x2 coupler 360, one of the outputs of 2x2 coupler 360 is passed directly to a second 2x2 coupler 362, while the other output is first passed through fiber section 364 (e.g., 10m of single mode fiber). One of the outputs of 2x2 coupler 362 is passed to section 352 of the 4x4 coupler, while the other output is passed to 2x2 coupler 366. 2x2 coupler 366 accepts
30 as its other input the corresponding feed from 2x2 coupler 368 of section 352. One output of 2x2 coupler stage 366 is passed directly to the final 2x2 coupler stage 370,

while the other output of 2x2 coupler stage 366 is first passed through fiber loop 372 (e.g., 60m of single mode fiber) prior to being input to 2x2 coupler 370. The two outputs of section 350 are passed to respective pump signal combiners 322 to couple the pump radiation energy with the fibers 326.

5 [0074] Specifically, an optical signal 324 propagates along a respective fiber 326 to a respective pump-signal combiner 322, where it is combined with a respective pump radiation profile. The pump radiation profile radiation counterpropagates with respect to a respective optical signal 324 and amplifies the signal 324 in the fiber 326. The pump assembly 301 also includes a number of other signal path processing devices,
10 e.g., one or more gain shaping filters 330 and isolators 332 and 334.

[0075] The signal path processing devices may also include an additional coupler (not shown) for coupling a co-propagating pump radiation profile to the optical data signals 324. Co-propagating pump radiation can be used to amplify the optical data signal as it leaves a repeater 16 so that launch power can be reduced. If so-called forward pumping
15 is employed in addition to or in place of contrapropagating (backward) pumping, then one or more co-propagating pump lasers can be added to one or more of the pump radiation sources 310. These co-propagating lasers can also be shared among the line assemblies as described, for example, in co-pending, commonly assigned, U.S. Patent Application Serial No. _____, entitled "Shared Forward Pumping in Coupled
20 Line Pair Architecture", to Thomas Clark et al., filed on May 29, 2001, the disclosure of which is incorporated here by reference, and by providing a second 4x4 coupler (not shown) to combine the forward pump outputs from each of the line assemblies.

[0076] As mentioned above, in addition to the pump lasers 314 themselves, the repeater also includes laser driver circuitry 460, monitoring and control circuitry 462, and power
25 supply circuitry 464 as generally shown in Figure 13. Therein, a shunt regulator 466 shunts a predetermined line voltage to a repeater 16 from power cable 468. DC-DC converters 464 downconvert the line voltage to a voltage usable by the monitor & control electronics 462 and laser current drivers 460. The monitoring and control circuitry 462 provides the capability for the terminals and repeaters to exchange
30 maintenance and control information over a communication channel. This communication channel can be implemented by modulation of the communication

envelope within which the high data rate WDM channels are carried or by providing a separate wavelength channel for this purpose. For more details regarding exemplary monitoring and control circuitry 462, the interested reader is referred to co-pending, commonly assigned U.S Patent Application Serial No. _____,

5 entitled "Redundant Repeater Monitoring Architecture", to John Mellert et al., filed on August 13, 2001, the disclosure of which is incorporated here by reference.

[0077] The monitoring and control circuitry 462 consumes a small percentage of the total power consumed by a high power repeater 16 according to the present invention. Together the pump lasers 314 and the laser current drivers 460 consume the majority of
10 the repeater's power. The total power consumed by high power, Raman amplification repeaters according to the present invention will depend upon many variables including the number of pump lasers used in each repeater and the anticipated spacing between repeaters 16 in the optical communication system (generally, greater spacing requires greater pump power). Another consideration in the total repeater power budget is the
15 manner in which the laser current drivers provide current to each pump laser pair. One possibility is to provide a fixed supply voltage from which each laser current driver provides each pump laser pair with sufficient drive current to generate a predetermined optical output power from the laser pair. This approach, however, is not the most power efficient approach, because each pump laser can require a different amount of
20 drive current to generate the predetermined optical output power. This phenomenon, and exemplary laser current drive circuits for more efficiently providing drive current to the large number of pump lasers found in high power repeaters according to the present invention, are described in more detail in co-pending, commonly assigned U.S. Patent Application Serial No. _____, entitled "Efficient Laser Current Drivers"
25 to Ronald E. Johnson, filed on October 3, 2001, the disclosure of which is incorporated here by reference. To summarize some of the results found in this patent application, Table 3 provides information regarding an exemplary 24 laser pair repeater intended to operate in a system having repeaters 16 spaced approximately 60 km apart.

[0078]	[0079] FIXED DRIVER SUPPLY VOLTAGE	[0080] VARIABLE DRIVER SUPPLY VOLTAGE
[0081] Line Current	[0082] 4A	[0083] 4A
[0084] Line Voltage	[0085] 200 V	[0086] 140 V
[0087] Shunt Regulator	[0088] ~8 W	[0089] ~8 W
[0090] DC-DC Conversion	[0091] ~157 W	[0092] ~77 W
[0093] Laser Drivers	[0094] ~219 W	[0095] ~67 W
[0096] Pump Lasers	[0097] ~380 W	[0098] ~380 W
[0099] Monitor & Control	[00100] ~29 W	[00101] ~29 W
[00102] Total Power	[00103] ~790 W	[00104] ~561 W

Table 3

- [00105] Unlike conventional systems, repeaters 16 according to the present invention
- 5 draw a very large amount of power due primarily to the number and output power of the pump lasers 314. However, as shown by the table above, efficient pump laser driver circuit designs can reduce the overall power consumption of a repeater significantly. Nonetheless Applicants believe that even with fewer than 24 laser pairs, reduced component redundancy and shorter distances between repeaters in a system, each
10. repeater will still draw in excess of 250 Watts – a dramatic increase over conventional repeaters. Moreover, repeaters according to the present invention which include 24 or more laser pairs, significant component redundancy and/or are designed to be spaced

more than 60 km apart, will likely draw more than 500 Watts and possibly more than 700 Watts each as evidenced by Table 3.

[00106] Given these exemplary optical and electronic schemes for Raman-amplified WDM repeaters according to the present invention, general design considerations associated with the mechanical aspects of line quad assemblies according to exemplary embodiments of the present invention include (1) minimizing temperature variances between ambient (e.g., sea water or sea floor) to the lasers and electronics in the line quad assemblies, (2) providing physical packaging that permits a predetermined number of line quad assemblies (e.g., 4) to be fit within a predetermined housing volume (e.g., as shown in Figure 3), (3) providing flexibility for growth and changes in optical/electronic architecture, (4) providing a layout which facilitates manufacturing of repeaters according to the present invention and (5) providing a minimum fiber bend diameter, e.g., of at least 50 mm.

[00107] The challenge of providing a mechanical design which accomplishes these design objectives is multiplied by the number of components needed to implement the aforescribed Raman amplification schemes. For example, depending upon the number of pump lasers employed to provide Raman gain to transmitted optical data signals, each line quad assembly can have 48, 56, 64 or more lasers 314. There can be 120 or more passive optical components, e.g., pump radiation combiner 312 components, 4x4 coupler 318 components, pump signal combiners 322, gain shape filters 330, fiber bragg gratings, etc. A large amount of optical fiber (e.g., 1000-2000m) is used to interconnect the pump lasers 314 and the passive optical components, which interconnectivity requires a large number of splices to be made between the optical fibers attached to each component. Additionally, space needs to be reserved within the packaging to wind up excess (slack) fiber between components. The line quad assemblies also need space for one or more power supplies, a backplane for electronic and power interconnection, laser current driver circuitry, monitoring and control circuitry.

[00108] These, and other, design considerations are accommodated by the exemplary structures described below and illustrated in Figures 14-24. Generally speaking each line assembly 400 according to this exemplary embodiment includes one pump

radiation source 310 (or two if bidirectional pumping is employed), one pump radiation combiner 312, a portion of the 4x4 coupler 318 (or portions of two 4x4 couplers with forward pumping), one set of signal path components, e.g, pump signal combiner 322, gain shape filter 330 and isolators 332, 334, and associated drive, power, monitoring and control circuitry.

[00109] According to a first exemplary embodiment, each line assembly 400 is fabricated as a rectangular frame 403 having a number of component containing structures mounted thereon, as well as electrical and optical interconnects, as seen in Figure 14. Initially an overview of the component containing structures in each line assembly will be provided, followed by more detailed information regarding each. Beginning with the top side 401, the line assembly 400 includes fiber bragg grating (FBG) containing assemblies 404, which may optionally have heating units associated therewith. These FBG assemblies 404 are used to contain the devices which act as wavelength lockers for each pump laser 314 as described above. The line assembly 400 also includes a printed circuit board 406 on which the pump lasers 314 are mounted and which carries the laser driver circuitry, as well as monitoring and control circuitry for the pump lasers. Each line assembly 400 further includes space for a power supply (not shown) to power the pump lasers 314 and other circuitry. One power supply 408 can be shared among the four line assemblies 400 in each line quad, or multiple power supplies (e.g., one on each line assembly) can be provided for redundancy.

[00110] Pump combiner assemblies 410 contain the pump beam combiner components and pump wavelength combiner components associated with pump radiation combiners 312. Both the top side 401 and the bottom side 402 of a line assembly can include spaces 412 for winding and excess fiber associated with optical component interconnects. These spaces can be oval in shape to accommodate a "figure eight" winding pattern at the minimum fiber bend diameter. Moreover, the shape and size of the spaces 412 can be determined based upon the manufacturing technique selected for winding the excess fiber, e.g., a manual or automated process. One example of an automated tool for winding excess fiber is described in co-pending, commonly assigned U.S. Patent Application Serial No. _____, entitled "Automated Fiber Winding Device", to Brent Pohl, filed on August 13, 2001, the disclosure of which is

incorporated here by reference. The bottom side 402 of line assembly 400 can also include a cassette 414 for holding the components and fiber associated with the signal path processing for the optical data fiber 324 associated with a particular line assembly 400. As mentioned above, this can include isolators 332 and 334, one or more gain
5 shape filters 330, a pump signal combiner 322, as well as other components. A cassette 416 holds 4x4 coupler components associated with one section thereof (e.g., section 350 or 352 as described above) and the associated fiber. Fiber ways 418 are formed at the end of line assemblies 400 in order to provide a convenient routing mechanism for optical fibers which connect optical components mounted on sides 401 and 402 with
10 one another. Each line assembly also has a dovetail groove 420 formed on onside thereof, which groove is used for routing fiber and connection to the inner frame 203 as will be described below.

[00111] Having briefly described the packaging layout of an exemplary line assembly 400 according to the present invention, each of the component containing structures
15 which are affixed to the line assembly frame will now be described in more detail. Beginning with the Fiber Bragg grating containers 404, various alternatives are possible. Since the wavelength locking functionality of Fiber Bragg gratings is temperature dependent, it may be necessary to provide a thermally controlled environment for these components. If so, the Fiber Bragg grating containers 404 can be
20 fabricated as, or include, thermally controlled packages an example of which is provided in Figure 15. Therein, the package 430 includes a thermally conductive layer 432, such as a conductive elastomer, that is used to mount the Fiber Bragg gratings. For example, slits 434 could be provided in the thermally conductive layer 432 for mounting the Fiber Bragg gratings. A temperature alteration device 436, e.g, a heating
25 unit or a cooling unit, is arranged adjacent to the thermally conductive layer 432 and the Fiber Bragg gratings mounted thereon, so that the temperature alteration device 436 can control the ambient temperature around the components.

[00112] If the temperature alteration device 436 is a heater, then a heat spreading layer 438 is provided between the heater 436 and the thermally conductive layer 432 so that
30 the heat generated by the heater 436 is evenly applied to the thermally conductive layer 432 and to the environment of the optical components mounted therein. If the

temperature alteration device 436 is a cooling unit, then layer 438 is a conductor having high performance thermal conducting properties to conduct the heat away from the optical components. A controller (not shown) is also provided to control the heating and cooling provided by the temperature alteration device 436. Layer 440 is provided to encapsulate the thermally conductive layer 432 (with the optical components mounted thereon), the temperature alteration device 436, the controller, and the heat spreader 438, and may either be an insulator or a good thermal conductor depending upon whether the temperature alteration device 436 is a heater or a cooling unit, respectively. An external casing (or outer package) 442 can also be provided to encapsulate the remaining layers. For more details regarding exemplary Fiber Bragg component containers, interested readers are referred to co-pending, commonly assigned, U.S. Patent Application Serial No. _____, entitled "Packaging Structure for Optical Components", to Lowell Seal et al., filed on October 3, 2001, the disclosure of which is incorporated here by reference.

[00113] An exemplary line assembly printed circuit board (PCB) 406 is illustrated in Figure 16. Therein, it can be seen that the PCB 406 includes first and second PCBs 450 and 452 sandwiching a core board 454. The PCB 452 has openings formed therein which permit the lasers 314 to be directly mounted to the core board 454, which is tapped for this purpose as seen in area 456. Core board 454 can, for example, be formed of 3-6 mm of copper and provides a mechanism for conducting the heat generated by the lasers 314 out to the pressure vessel 200. Although only four lasers 314 and sixteen areas 456 are illustrated as populating the PCB 452, those skilled in the art will appreciate that more or fewer lasers can be provided for therein depending upon the Raman pump design considerations described above. A hybrid signal connector 458 is also provided for conveying power and command signals to the circuitry provided thereon.

[00114] Referring again to the line assembly 400, an exemplary optical fiber packing and containment container structure which can be used, for example, to hold the pump combiner assemblies 410, signal path component assemblies 414 and 4x4 coupler component assemblies 416, is illustrated in Figure 17(a). This container enables excess optical fiber to be wound and stored in a thin structure which allows for multiple entry

and exit points, eliminates torsional loading of the fiber and minimizes the volume needed for fiber storage (as compared to other devices). Those skilled in the art will appreciate that, in addition to those components mentioned above, containers according to this exemplary embodiment of the present invention, can also be used to manage various other types of opt-mechanical and electrical components.

[00115] In Figure 17(a), cassette 470 includes a plurality of cavities 472 for holding optical components 473 and an area 474 for holding one or more stackable, fiber winding trays 476. Optical components 473 can be secured within each cavity 472 using, for example, clips or adhesives. Each cavity 472 has a pair of fiber routing openings that lead to fiber routing paths 478. The fiber routing paths 478 provide an easy mechanism for routing the individual optical fibers that connect each component to other components in the repeater 16. Excess fiber 480 which remains after splicing two of the optical components together can be wound on the stackable fiber winding trays 476.

[00116] By separating the optical fiber winding trays 476 from the discrete optical components, and providing plural trays, access is provided to rework the optical fiber (e.g., in the case that a splice needs to be redone) without disturbing the components and preserving the containment of the remaining optical fiber. Each fiber winding tray 476 has a plurality of fiber retaining clips 482 which retain the wound fiber 480 in the tray 476. Among other things, these retaining clips 482 minimize the adverse effects of vibration, shock and handling on the fiber. Clips 483 toward the center of the tray 476 permit the fiber 480 to be wound in a “figure 8” shape. This winding shape for excess fiber 480 is particularly advantageous because it avoids adding twists to the fiber, which twists would be induced by coiling the excess fiber using a circular or oval pattern. Cutouts 484 are also formed in each tray to provide exit points for the fiber 480. Providing a large number of exit points 484 permits manufacturing flexibility given the random length of excess fiber to be wound in tray 476 after splicing operation are performed. The fiber 480 can exit the cassette via any one of a number of exit ports 486. Once the components and fiber are secured within the tray 476, it can be closed by attaching cover 488 thereto, e.g., using screws. The completed cassette 470 can then be attached to the line assembly in its designated location.

[00117] Another exemplary embodiment of fiber winding tray 476 is depicted in Figure 17(b). Therein, the fiber winding tray 476 has more fiber retaining clips 483 than the fiber winding tray of Figure 20, as well as two additional center clips 490. The additional center clips 490 permit the winding of two overlapping figure 8's in the winding tray 476. The fiber winding tray 476 of Figure 18 also has an entry/exit way 494 through which fiber enters and leaves the fiber winding tray 476 as opposed to cutouts 484. This feature reduces torsional loading on the optical fiber, particularly while handling multiple trays 476.

[00118] Many variations and adaptations of the optical component cassette 470 with stackable fiber winding tray(s) 476 will be apparent to those skilled in the art. Another example is provided as Figures 18(a) and 18(b). Therein, an assembled optical component tray 600 is shown in Figure 18(a) with a removable fiber winding tray 602 and an optical component holding area 604. A number of optical fiber guide grooves 606 are provided through which optical fiber can be routed to connect optical components (not shown) disposed in optical component holding area 604. Optical fibers can enter and exit the optical component tray 600 via openings 608. In this exemplary embodiment, the stackable fiber winding tray 602, also shown enlarged as Figure 18(b), includes crescent shaped guides 612, oval spool guides 614, clip guides 616 and detents 618. Elements 612, 614 and 618 cooperate to accommodate four different winding paths in winding tray 602. Specifically, as seen in Figure 18(c), winding tray 602 accommodates a large oval winding pattern, a small oval winding pattern, a figure eight winding pattern and circular winding patterns, each of which is designed to provide the minimum bend diameter, e.g., 50 mm. These different winding paths have relatively different inside and outside diameters which, in turn, provide for a wide variety of winding path lengths, to permit excess optical fiber of varying lengths to be wound on fiber winding tray 602. Elements 616 hold fusion splice protector sleeves, also known as "splints", firmly in place when splinted splices are used to join optical fibers.

[00119] The optical component holding area 604 can include cavities defined by rigid walls formed in the optical component holding area 604, e.g, similar to those shown in Figure 17(a) or can employ an elastomeric retaining device 620 as seen in Figures 18(d)

and 18(e). The elastomeric retaining device provides a deformable, friction fit for retaining optical components, e.g., component 621, so that the optical components are not subjected to mechanical or thermal stress. In these exemplary embodiments, the elastomeric retaining device 620 is formed as a series of alternating openings 622 and at least partially hollow tubes 624 which permit optical components having a range of sizes, e.g., diameters of 3-6 mm, to be retained therein. The elastomeric retaining device 620 can be glued or otherwise affixed to the optical component holding area 604.

[00120] The optical component holding area 604 can also be integrated with the fiber winding tray 610. For example, as seen in Figure 18(c), a portion of the optical component holding area 604 is integrally formed with the fiber winding tray 610 and includes three sets of optical fiber guides 606. In this way, reworking of connections or replacement of components associated with a subset of the optical components disposed within the optical component tray 600 can be performed by removing the tray 610, thereby isolating the remaining components and fiber and rendering the reworking process less susceptible to error.

[00121] Having described the mechanical layout of an exemplary line assembly according to exemplary embodiments of the present invention, the interconnections between the four line assemblies within a line quad assembly will now be discussed.

With reference to Figure 19, two line assemblies 500 and 501 are stacked and connected as a line pair assembly 504. Note that the PCBs 406 associated with each line assembly are disposed on opposite sides of the line pair assembly 504. In this way, the heat generated by the lasers 314 mounted on each line assembly 500 and 501 is further distributed within the repeater 16. Near the middle of each line assembly 500, 501 are fiber ways 506 for permitting optical fibers to connect components disposed on different line assemblies, e.g., components within 4x4 coupler subassemblies 416 connected to different line assemblies. These fiber ways 506 are better seen in the enlarged view of Figure 20. Figure 21 illustrates two line pair assemblies 510 and 512 being assembled into a single line quad assembly 514. A backplane 516 provides electronic and power/ground interconnections. Fiber cover 518 protects the fibers routed between line assemblies and line pair assemblies, as well as providing a

mechanism to secure all four line assemblies together. As seen in Figure 22, fiber ways 550 provide guides for routing optical fibers between line pair assemblies. Also seen in Figure 22 are posts 552 which provide electrical connections via solder, crimp or screw connections for power cables 554 to provide DC electrical power to the line quad assembly 514.

[00122] Figure 23 shows an exemplary technique for provisioning a repeater 16 with four line quad assemblies 514 into the inner frame structure 203 of the pressure vessel 200. Those skilled in the art will appreciate that one, two, three or four line quad assemblies may be mounted therein, depending upon how many optical fiber pairs are being supported in the optical communication system. Various mechanisms can be used to secure the line quad assemblies 514 therein. According to one exemplary embodiment of the present invention, the line assemblies 400 each have a dovetail groove 560 formed therein as shown in Figure 24. For the two outer line assemblies in each line quad assembly, e.g., 562 and 564, the dovetail groove 560 is used to secure the line quad assembly to the inner frame 203. For example, the dovetail groove in line assembly 562 can be slid into a mating engagement with abutment 570 in the inner frame 203. This engagement can be secured using, for example, a spring or a wedgelock 572 positioned within the dovetail groove of line assembly 564. The spring or wedgelock device 572 presses against the inner frame 203 and the dovetail groove of line assembly 564 using, e.g., 650 lbs of force, to lock its line quad assembly in place. Additional details regarding exemplary dovetail grooves and wedgelock devices which can be used in conjunction with high power repeaters according to the present invention can be found in commonly assigned, co-pending U.S. Patent Application Serial No. _____, entitled "Use of Dovetail Slides and Wedge Locking Devices for Mounting", to Lowell Seal, filed on September 12, 2001, and co-pending U.S. Patent Application Serial No. _____, entitled "Integrated Wedge Lock and Elastic Member", to Bob Adams et al., filed on September 10, 2001, the disclosures of which are incorporated here by reference.

[00123] Those skilled in the art will appreciate that the foregoing exemplary embodiments provide ground breaking new designs in the area of repeater technology for underwater optical communication systems. The foregoing techniques enable high

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